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Strings, quantum fields and the UV landscape

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Introduction

• Gravity is the oldest known but least understood force.

• The biggest puzzles today (dark energy and the cosmological constant problem) have gravity as their weak link.

• The major clash seems to be between gravity and the quantum theory. Both issues are summarized in: "What is quantum (gravity+matter)".

• A proposal will be entertained that at the conceptual level rests on the Aristarchus-Copernicus (AC) view that we are (probably) not at the center of the "universe".

• There are several ingredients:

♠ The H. Nielsen postulate (from the '80s) that the QFT describing physics in the UV is "large" and (almost) random.

♠ The fact that string theories (ST) generically contain many "hidden sectors" that can be at best barely visible to us.

♠ The gauge-gravity correspondence that provided a fresh look both at gauge theories and the gravitational/string forces.

♠ The realization that the gauge-gravity correspondence bring in new light at the relation between traditional QFT and gravity as realized in string theories.

The logic

• Gravity is an avatar of (closed) string theories.

• It can be generated by many types of CFTs, in particular by 4d QFTs (as suggested by generalizations of AdS/CFT).

• Assumption 1: The complete description of physics is via UV-complete 4d QFTs.

• Assumption 2: The UV QFT is enormous and “random”.

• Gauge Symmetry defines “distinct sectors” associated to gauge groups. Such distinct parts of this QFT are communicating via massive ”bifundamental messager” fields.

• The Standard Model is a tiny piece of the UV QFT.

• The physics they communicate to the Standard Model depends crucially on the ”size” of the QFT

• A important avatar of the presence of large QFTs in the UV is the appearance of “gravity” (and PQ axions) in the SM.

The couplings of the SM

• We have learned in the past decades that the couplings of the QFT of the SM may be "dynamical"

$$S_{SM} \sim \int d^4x \;\; T^{\mu\nu,\rho\sigma} \; Tr[F_{\mu\nu}F_{\rho\sigma}] + {e^\mu}_a \bar{q}(\gamma^a(i\partial_\mu + A_m))q + H\bar{q}q + \theta F \wedge F$$

$$T^{\mu\nu,\rho\sigma} \sim \frac{\sqrt{g}\;\, g^{\mu\rho}g^{\nu\sigma}}{4g_{YM}^2} \to (\text{metric}) \quad , \quad H \to \quad \text{Higgs} \quad , \quad \theta \to \text{PQ} \quad \text{axion}$$

• We believe that such "coupling constants are dynamical, but we are not entirely sure if they are quantum mechanical.

• String theory is another theory where coupling constants are dynamical(+quantum mechanical) variables.

QFT vs ST

• Every QFT has a generating functional of correlation functions.It is obtained by coupling (an infinite number of) sources to ALL (gauge-invariant/physical/non-redundant) operators of the theory.

$$e^{-W[J_i]} \equiv \mathcal{N}^{-1} \int \mathcal{D}\phi_i \;\; e^{-S[\phi_i, J_i]} \quad , \quad S[\phi_i, J_i] \equiv \sum_i \int d^D x \; O_i(\phi) J_i(x)$$

• Its Legendre transform is the (generalized) quantum effective action.

• Among the sources, there are many spin two fields $g^i_{\mu\nu}$ that couple to the spin-two operators of the theory.

• There are many subtleties with the definition of $W[J]$ but the following can be shown:

♠ All global symmetries of the QFT are local symmetries of $W[J]$. In particular translation invariance of the QFT, implies diffeomorphism invariance of $W[g_{\mu\nu}, J]$, internal symmetries become gauge symmetries.

♠ A priori the sources $J_i(x)$ are non-dynamical variables.

♠ If we integrate out multi-trace operators (eg. $O_2(x) = O(x)^2$, $O_3(x) = O(x)^3$ etc) then the sources for the single-trace operators become (quantum) propagating fields.

String theory is the dynamics of sources of QFT.

E. Kiritsis, S. S. Lee

♠ Implementing the Wilsonian RG flow, it generates an extra dimension in the theory of sources (string theory).

♠ All of the above, of course were seen explicitly in concrete examples of AdS/CFT.

♠ At large-N, the (quantum) interactions of sources are weak.

♠ At strong coupling the source effective action is local. Non-locality is generated by "long operators", $O_L \sim Tr[\phi^n]$ with n large. (a long string with n "bits")

The UV Landscape of 4D gauge theories

♠ Our goal will be to derive (observable) gravity from the UV landscape of 4D gauge theories.

• We postulate that the UV theory is a 4D QFT (gauge theory) that is

1. Enormous and "Random". (I do not enter details on "statistics" here.)

H. Nielsen

2. UV complete (Conformal or AF). This does not prohibit IR free theories at low energies.

• The gauge group structure is $\prod_i G_i$. The SM group is a tiny part of this.

• Generically the G_i are groups of large rank. Focus on $SU(N_i)$ but conclusions are general.

• UV completeness is a very strong constraint. It is more stringent for larger N_i. Matter can only be in the representations, (adjoint, $\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$ and $\Box\Box$, $\Box$).

• Even at strong coupling, other representations are not allowed for large enough N_i. Otherwise they can be vectors, fermions or scalars.

• An important issue is communication between groups:

1. Matter ϕ_{ij} charged under both (G_i, G_j). Such fields must have non-zero (large) mass. They are the messengers.

For $N_i \gg 1$ they must be generically bifundamentals to not spoil UV completeness (fundamental messengers). Sometimes, for small rank, adjoints, and (A,S) reps can also be allowed (exceptional messengers). When integrated out, they generate double/multiple trace interactions between G_i and G_j.

2. Double trace interactions in the UV. These can be relevant or marginal in a few cases of strongly coupled CFTs. At low energy they look similar to 1. but not at high energy.
At large N_i they lead to boundary-boundary interactions of independent string theories.

Kiritsis ('05), Aharony+Clark+Karch ('05), Kiritsis+Niarchos ('08)

• Such interactions must be relevant or marginal, and are therefore rare as they require "gauge-invariant" operators with $\Delta < 2$. Moreover, many are unstable (like in N=4 sYM case).

♠ There are groups that communicate directly with the SM, and groups that do not. The ones that are relevant (to leading order) are those that do.

The leading IR interactions

• A generic simple group factor G_i of the UV theory is characterized by a rank N_i, and a gauge coupling constant λ_i as well as other couplings (Yukawa, quartic etc).

• If the theory is AF, then the spin-two glueball (as well as others) will be massive. Its mass is given by the characteristic scale Λ_i generated by dimensional transmutation. Unless this mass is unnaturally low, such glueballs that will be eventually weakly coupled to the SM (via gravitational messengers) will not be easily visible.

• If the theory is conformal, then there is a continuum of spin-two modes and these will survive in IR physics. The conclusion is that (not surprisingly) only CFTs can give effects in the SM at the extreme IR.

• Two more factors are important: λ_i and N_i.

• Intuition from AdS/CFT suggests that at weak coupling, RG instabilities are generic and important.

• Relevant operators generically destroy the conformal invariance in the IR, and therefore the chance that the CFT is "visible" to other sectors at low energy.

• A stable CFT has no relevant operators. Weak coupling CFTs have ALWAYS, many relevant operators (fermion bilinears, scalar bilinears and trilinears etc.).

• Supersymmetry does not help. The expectation is that stable CFTs will have strong coupling.

• Large N CFTs will also dominate smaller N CFTs. The reason is that they are IR stable against messenger perturbations. There is also an entropic dominance. In a CFT at any $T > 0$, the entropy scales as $\mathcal{O}(N^2)$.

• The conclusion is that the leading relevant IR couplings to the SM will come from a QFT that

1. Has messenger couplings to the SM
2. Is a CFT
3. Has the largest possible N and the largest possible λ.

It has therefore a dual realization in terms on AdS geometry in more than 4 dimensions. The (emergent) dimensionality depends on the details of that CFT, is at least 5 and can be more than 10.

A messenger-friendly SM

• What kind of gravitational messengers are needed? What kind of SM structure is needed for this?

• As mentioned, the messengers must be bi-fundamentals for UV completeness They must have both bosons and fermions to couple to all SM particles.

• They should contain in particular vectors in order to have a mild impact on β-functions.

• We assume $A^i_{\mu,\alpha}, \chi^i_\alpha$, where i is a SM fundamental index, and the hidden SU(N) color index is α.

• In order to have RENORMALIZABLE couplings of every SM field to two gravitational messenger fields, (for hidden color invariance) the SM must be written in a way that all representations are of the "bifundamental type".

• This can be done in several ways that have been classified when the embeddings of the SM spectrum in string-theory orientifolds was considered.

Anastasopoulos+Dijkstra+Kiritsis+Schellekens ('06)

• An orientable example is (including massive anomalous U(1)'s), with $Y = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$.

particle	$U(3)_c$	$SU(2)_w$	$U(1)$
$Q(\mathbf{3},\mathbf{2},+\frac{1}{6})$	V	V	0
$U^c(\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	$\bar{V}$	0	V
$D^c(\bar{\mathbf{3}},\mathbf{1},+\frac{1}{3})$	$\bar{V}$	0	$\bar{V}$
$L\ (\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$\bar{V}$	V
$e^c(\mathbf{1},\mathbf{1},+1)$	0	0	$\bar{S}$
$\nu^R(\mathbf{1},\mathbf{1},0)$	0	A	0
$H(\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$\bar{V}$	V

• If we denote the SM particles as B_μ^{ij}, q^{ij}, H^{ij} then the relevant couplings are

$$\bar{q}^{ij}\gamma^\mu\chi_i^a A_\mu^{a,j} \quad , \quad B_\mu^{ij}\bar{\chi}_i^a\gamma^\mu\chi_j^a \quad , \quad H^{ij}\bar{\chi}_i^a\chi_j^a$$

• There are several subtleties with anomalies and anomalous U(1)'s that may have observable consequences.

On the equivalence principle (I)

• In the absence of scalars in the SM, the issue of universality of the gravitational couplings is trivial.

• The metric couples to all spin two operators.

• Those that have dimension > 4 have a coupling suppressed by the gravitational messenger mass $\Lambda_{mes} \sim M_P$.

• If there are relevant couplings in the SM, then there could be "anomalous" gravitational couplings proportional to positive powers of Λ_{mes}.

• The SM (with a natural/composite Higgs) does NOT have relevant couplings.

• Marginal scalar operators of the large-N CFT can spoil the equivalence principle (more later).

Maldacena vs Randall+Sundrum

• After integrating out the messagers at $E \ll \Lambda_{mes}$, a caricature of the physics is given by a probe (stack of) branes (eg the SM) in a AdS_5-like background.

$$S_{CFT} = M_5^3 \int d^5x \sqrt{g} \left[R_5 + \frac{12}{\ell^2} \right] + S_{SM}(\hat{g}) \quad , \quad (M_5 \ell)^3 \simeq N^2$$

This looks like Randall+Sundrum but:

• There is NO UV cutoff in the 5d-geometry

• There is no IR cutoff.

• There is no 4d-graviton zero mode as in RS.

• The probe brane stack is at a radial position associated with its energy scale. (as first considered by Lykken+Randall)

• This radial position is the mass of the messengers, Λ_{mes}. (This mass should be due to an expectation value).

• Λ_{mes} is a cutoff for 5d-gravity+SM.

Although there is an (AdS) geometry above Λ_{mes}, the SM does not "see it" as above Λ_{mes} it is not directly coupled to gravitons but only to the messengers.

DGP Revisited

• The main question now is: why gravity felt by the SM particles is 4d? The idea of an answer was given by

Dvali+Gabadadze+Porrati ('00)

• Loops of SM particles generate a four-dimensional Einstein term

$$S_{\text{grav}}^{\text{SM-loops}} = \int d^4x\sqrt{\hat{g}}\ \left[\Lambda_{mes}^4 + \Lambda_{mes}^2 R_4 + \log(\Lambda_{mes}^2) R_4^2 + \cdots\right]$$

The natural cutoff is the gravitational messenger scale.

• The total gravity action is

$$S_{grav} = M_5^3 \int d^5x\sqrt{g}\left[R_5 + \frac{12}{\ell^2}\right] + S_{\text{grav}}^{\text{SM-loops}}$$

• The static graviton propagator (on the SM "brane") is (we ignore for the moment the Λ_{mes}^4)

$$G \sim \frac{1}{M_5^3}\frac{1}{|\vec{p}| + r_c\vec{p}^2} \quad , \quad r_c = \frac{\Lambda_{mes}^2}{M_5^3}$$

• At long distances $|\vec{p}|r_c \ll 1$ gravity is 5d: $V_{grav} \sim \frac{M_5^3}{r^2}$.

• At short distances $|\vec{p}|r_c \gg 1$ gravity is 4d: $V_{grav} \sim \frac{\Lambda_{mes}^2}{r}$.

$$\text{Therefore :} \qquad M_{Planck} \sim \Lambda_{mes} \sim 10^{19} \ \text{Gev}$$

• The transition (length) scale is

$$M_c = \frac{1}{r_c} \lessapprox 10^{-33} \text{ eV}$$

• In curved space (AdS_5) the story changes somewhat, but it turns out the physics remains 4d.

Kiritsis+Tetradis+Tomaras

The equivalence principle (II)

• We do not expect to have relevant operators, we may however have marginal scalar operators. (An example in N=4 is the dilaton $\to$ gauge coupling constant).

• Such operators will couple to the SM via the same gravitational messengers.

• They will correspond to scalar massless "gravitons". They might destroy the equivalence principle.

• The same SM quantum corrections will provide a localized effective action for them.

• (Unlike the graviton), nothing prohibits an induced mass for them.

$$S_{\text{induced}} = \Lambda^2_{mes} \int d^4x \sqrt{\hat{g}} \left[(\partial\phi)^2 + \Lambda^2_{mes}\phi^2 + \log(\Lambda^2_{mes})\phi^4 + \cdots \right]$$

Therefore they have Planck scale masses, and they are irrelevant for low scale physics. They do not violate the equivalence principle.

The axion

• There is always a single universal pseudoscalar marginal operator in the hidden group namely the instanton density $a \sim Tr[F \wedge F]$.

• Its dual bulk action is large-N suppressed (RR field, or θ angle)

$$S_a = \frac{M_5^3}{N^2} \int d^5x (\partial a)^2$$

• If the gravitational messengers generate a mixed anomaly $Tr[T_{\text{SM}_i} T_{\text{SM}_i} Q_{\text{m-chiral}}] = N \; I_i \neq 0$, then the messengers induce a coupling of the axion to the pseudoscalar densities

$$S_{PQ} = \sum_i \int d^4x \; a \; \frac{I_i}{N} \; Tr[F_i \wedge F_i]$$

• Loop effects of the SM gauge bosons generate a 4d-kinetic term for the axion but no mass term or potential.

$$\delta S_{PQ} = \sum_i I_i^2 \; \frac{\Lambda_{SM}^2}{N^2} \; (\partial a)^2 \quad , \quad f_{PQ} \sim \frac{M_{\text{Planck}}}{N}$$

• QCD instantons generate a potential for the axion as usual $V_a \sim \Lambda_{QCD}^4 \cos a$.

• An analogue of the DGP mechanism is at work here for the axion with potentially interesting consequences.

Hyper-unification

• We have some evidence suggesting "unification" of SM couplings around "M_{GUT}"

• This may be affected by intermediate sectors, but is suggestive.

• The massive messenger vectors must belong to spontaneously broken gauge groups, for renormalizability.

• The natural expectation is that at $\Lambda_{mes} \sim M_P$ or above the messenger gauge fields and the Large-N hidden group "unify".

• This automatically entails the unification/inclusion of the SM group.

• This is a unification of "matter" and gravity.

Outlook

• The postulates assumed (AC vision, randomness of UV QFT, gauge-gravity duality) do not predict/postdict any precise number (so far) but:

• They turn "upside down" our view of gravity and how it interacts with the Standard model.

• They "explain" the emergence of gravitational force which is semiclassical, and of "thermodynamic" nature.

• They suggest the UV degrees of freedom of gravity (the "partons" of the large N, strongly coupled CFT).

• They suggest that the universality of the gravity couplings is an IR "accident".

• They suggest why the PQ axion is as universal as gravity is.

• They suggest the presence of extra massive "anomalous" U(1) bosons in the SM.

• They paint a gravitational picture of the UV QFT in terms of super-structure (the hyper-universe) where small-N sectors (our universe) are small brane stacks floating in a (potential superposition) of semiclassical manifolds containing many such universes.

• They suggest that other CFTs with lower N may be visible in modifications of gravity.

• They suggest a mirage picture for cosmology.

• It remains to be seen whether these ideas will lead to a fruitful reconsideration of the mariage between QFT and gravity.

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THANK YOU!

String theory and Gravity

• String theories have been traditionally defined via 2-d σ-models.

• The string coordinates (bosonic or fermionic) are 2d-quantum fields.

• Continuum σ-models are CFTs and are parametrized by "coupling constants" that correspond to the massless (or tachyonic) string modes.

• The relevant couplings involve the σ-model coupling constant $\frac{\ell}{\ell_s}$ and g_s that controls string interactions BOTH at tree level and loops.

• In a sense, the "loop-expansion" is not inherent in the σ-model. It is an added ingredient. Also the space-time is "emergent": the coordinates are (2d) quantum fields and the metric+other fields are 2d coupling constants.

• Closed strings always include gravity. UV divergences are simply cutoff by the smart world-sheet cutoff of Riemann surfaces.

• The relevant conditions for conformal invariance have a simple expansion at weak σ-model coupling. For example, the dilaton β-function reads

$$\beta_\Phi = \left(D_b + \frac{1}{2}D_f\right) - D_{crit} + \frac{3}{2}\ell_s^2\left[4(\nabla\Phi)^2 - 4\Box\Phi - R + \frac{1}{12}H^2\right] + \mathcal{O}(\ell_s^4)$$

$D_{crit} = 26$ for the bosonic string and 15 for the fermionic strings.

• At weak coupling, conformal invariance imposes the critical dimension:

$$\left(D_b + \frac{1}{2}D_f\right) = D_{crit}$$

curvature corrections are small and the backgrounds are slowly varying.

• Subcritical strings, with $\left(D_b + \frac{1}{2}D_f\right) < D_{crit}$ quickly run to large curvatures and therefore to strong σ-model coupling. The relevant "flow" equations (summarized by the two derivative effective action) have AdS-like solutions.

• In the supercritical case with $\left(D_b + \frac{1}{2}D_f\right) > D_{crit}$ the equations have deSitter-like solutions.

Strings/Gravity from 4D gauge theories

• Strings emerge from higher-d QFTs in d=3,4 and maybe in d=6. I will focus in d=4 where the main QFT is a gauge theory coupled to fermions and scalars.

• Continuum string theories will emerge from conformal gauge theories.

• At weak coupling and large enough N, the main contributions to the β functions come from adjoints (orientable case)

$$\beta(g) = -\frac{g^3}{(4\pi)^2}\left\{\frac{11}{3} - \frac{2}{3}N_F - \frac{N_s}{6}\right\}N - \frac{g^5}{(4\pi)^4}\{34 - 16N_F - 7N_s\}\frac{N^2}{3} + \cdots$$

with N_f Majorana fermions and N_s scalars in the adjoint of SU(N). We may add $\square, \begin{smallmatrix}\square\\ \square\end{smallmatrix}, \square\square$ and they always contribute positively.

• Higher than "bi-fundamental" representations make the theory IR-free at sufficiently large N.

• The vanishing of the one-loop piece is analogous to being in the critical dimensions in the σ-model definition of string theory. There are two special cases:

$N_F = 4, N_s = 6$

that includes the case of $\mathcal{N} = 4$ sYM. The higher loop contributions to the β-functions are cancelled by Yukawa and quartic scalar contributions.

• The maximal global symmetry in this case is $SO(6)$, realized in a minimal geometrical fashion on an S^5.

• The "emergent" geometrical dual holographic picture (at large N) involves also AdS_5 that geometrically realizes the conformal invariance. The gauge theory develops "extra dimensions" to total of 10. This is type-II superstring theory.

Maldacena ('97)

• The theory contains fermionic gauge invariant operators, and therefore there are space-time fermions in the string theory.

• There are other fixed points with $N_F = 4, N_s = 6$ that should also be described by the same superstring theory.

$N_F = 0, N_s = 22$

• This is another special case. Although one-loop conformal, higher terms in β functions can only stabilized at strong coupling (presumably).

• The maximal global symmetry is SO(22), and in a holographic dual it should geometrically (and minimally) realized by an S^{21}.

• Together with the conformal factor, the backgrounds makes $AdS_5 \times S^{21}$ and is 26 dimensional.

• The associated gauge theory seems to correspond to **a bosonic string**. There are only bosonic gauge-invariant operators. This is however a false expectation. It is most probably a fermionic superstring with no space-time fermions.

• Therefore the theory is more like the Type-0 Theory. It is not obvious that this is the superstring behind the $N_s = 22$ case.

• There are also Bank-Zaks-like fixed points in 25 dimensions involving the condensation of flavor branes, and they may be related.

There are other cases that are "critical", for example:

- $N_s = 18, N_f = 1$. The maximal symmetry here is $O(18)$ as the fermionic U(1) is anomalous. The expectation therefore is that in the most symmetric case the background will be $AdS_5 \times S^{17}$ and may correspond to a novel fermionic non-supersymmetric string theory in 22 dimensions.

- $N_s = 14,\ N_f = 2$. The maximal symmetry is O(14) for the bosons and SU(2) for the fermions. As there are always Yukawas in this case, the SU(2) will be embedded in O(14), and the expected internal space will probably be a squashed S^{13} leading to a fermionic non-supersymmetric string theory in 18 dimensions.

- $N_s = 10,\ N_f = 3$. The maximal symmetry is O(10) for the bosons and SU(3) for the fermions. As there are always Yukawas in this case, the SU(3) will be embedded in O(10), and the expected internal space will probably be a squashed S^9 leading to a fermionic non-supersymmetric string theory in 14 dimensions.

Etc...

• The evidence for such more exotic fermionic string theories is so far slim, but can be made more solid by investigating the RG patterns of appropriate gauge theories.

• The $a - c$ argument from holography, together with perturbative β-functions suggests that the only weakly-coupled theories are the ten-dimensional ones.

• We can go further by allowing the 4d gauge couplings to be space-time dependent. The β-functions are not known except is the simplest possible case of constant but non-Lorentz invariant context. (H. Nielsen, ('78))

Generalized Bank-Zaks fixed points

Consider the general β function coefficients and set

$$\frac{11}{3}-\frac{2}{3}N_F-\frac{N_s}{6}=a \quad , \quad 0\leq a\leq \frac{11}{3}$$

and choose the number of flavors so that

$$b_1=aN-\frac{2}{3}n_F-\frac{n_s}{6}=\epsilon>0 \quad , \quad \epsilon\ll N$$

$$b_2=-\left[\frac{50+4N_F+5N_s}{4}N^2+\frac{n_s}{4N}(N^2-3)\right]+\mathcal{O}(\epsilon)<0$$

For $\epsilon\to 0$ there is a Bank-Zaks fixed point at

$$\frac{\lambda_*}{(4\pi)^2}=\frac{g_*^2 N}{(4\pi)^2}\simeq\frac{4N\epsilon}{(50+4N_F+5N_s)N^2+\frac{n_s}{N}(N^2-3)}$$

The maximum number of emerging dimensions is obtained by $N_F=0, N_s=21$, where $a=\frac{1}{6}$ and $\epsilon=\frac{N}{6}-\frac{2}{3}n_F-\frac{n_s}{6}$. Take $n_F=0$ and $n_s=N-1$, so that $\epsilon=1$ and

$$\frac{\lambda_*}{(4\pi)^2}\simeq\frac{4}{155N+(N-1)\frac{N^2-3}{N^2}}\simeq\frac{1}{39N}+\mathcal{O}(N^{-2}) \quad , \quad RETURN$$

Bank-Zaks-YM theories

$$\beta_{BZ}(\widehat{\lambda}) = -\epsilon\widehat{\lambda}^2 + b_*\widehat{\lambda}^3 + \cdots \quad , \quad \left(\frac{\epsilon}{b_*\widehat{\lambda}(\mu)} - 1\right) e^{\frac{\epsilon}{b_*\widehat{\lambda}(\mu)}} = \left(\frac{\mu}{\Lambda}\right)^{\frac{\epsilon^2}{b_*}}$$

In the BZ region, $\epsilon = \mathcal{O}\left(\frac{1}{N}\right) \ll 1$, $b_* = \mathcal{O}(1)$. We have

$$\widehat{\lambda}(\mu \to \infty) = \frac{1}{\epsilon \log \frac{\mu}{\Lambda}} + \cdots \quad , \quad \widehat{\lambda}(\mu \to 0) = \frac{\epsilon}{b_*} - \frac{e^{-1}\epsilon}{b_*}\left(\frac{\mu}{\Lambda}\right)^{\frac{\epsilon^2}{b_*}} + \cdots$$

- We now consider the fundamentals having a common mass m.

- For $\mu \gg m$ the flavors are effectively massless, and the flow is as above.

- Below m however the flavors decouple and the theory is asymptotically free with a one-loop β function $b_0 = \mathcal{O}(1)$.

• For $\mu \ll m$ we obtain

$$\beta_{YM}(\hat{\lambda}) = -b_0\hat{\lambda}^2 + \cdots \quad , \quad \frac{1}{\hat{\lambda}(\mu)} = \frac{1}{\hat{\lambda}(m)} + b_0 \log\frac{\mu}{m}$$

$$\left(\frac{\epsilon}{b_*\hat{\lambda}(m)} - 1\right) e^{\frac{\epsilon}{b_*\hat{\lambda}(m)}} = \left(\frac{m}{\Lambda}\right)^{\frac{\epsilon^2}{b_*}}$$

In this case the theory in the ultimate IR is AF, and the coupling is driven to infinity. We can calculate the effective IR scale associated with the AF running of the coupling as

$$\Lambda_{IR} = m\ e^{-\frac{1}{b_0\hat{\lambda}(m)}}$$

• For $\frac{m}{\Lambda} \ll 1$, we obtain

$$\Lambda_{IR} \sim m\ e^{-\frac{b_*}{b_0}\frac{1}{\epsilon}} \ll m \quad , \quad \frac{m}{\Lambda} \ll 1$$

Bosonic string or superstring?

• Consider the axion a dual to $Tr[F\wedge F]$. We can show that it must come from a RR sector.

In large-N$_c$ YM, the proper scaling of couplings is obtained from

$$\mathcal{L}_{YM}=N_c\; Tr\left[\frac{1}{\lambda}F^2+\frac{\theta}{N_c}F\wedge F\right]\quad,\quad \zeta\equiv\frac{\theta}{N_c}\sim\mathcal{O}(1)$$

It can be shown (Witten, '79)

$$E_{YM}(\theta)=N_c^2\;E_{YM}(\zeta)=N_c^2\;E_{YM}(-\zeta)\simeq C_0\;N_c^2+C_1\theta^2+C_2\frac{\theta^4}{N_c^2}+\cdots$$

In the string theory action

$$S\sim\int e^{-2\phi}\,[R+\cdots]+(\partial a)^2+e^{2\phi}(\partial a)^4+\cdots\quad,\quad e^{\phi}\sim g_{YM}^2\quad,\quad \lambda\sim N_c e^{\phi}$$

$$\sim\int\frac{N_c^2}{\lambda^2}\,[R+\cdots]+(\partial a)^2+\frac{\lambda^2}{N_c^2}(\partial a)^4+\cdots\quad,\quad a=\theta[1+\cdots]$$

RETURN

Many string universes and their mixing

• What is the dual (geometrical) description of two strongly coupled, large-N CFTs, $CFT_{1,2}$?

• The product of two AdS spaces with their own string theory on them

$$AdS_1 \times X_1 \cup AdS_2 \times X_1$$

(with in general different, M_5, ℓ_{AdS}, N).

• They share a common boundary.

• They contain two distinct massless NON-interacting gravitons.

• We now couple such CFTs by (multiple trace) operators, $h\ O_1 O_2$?

• This is the $m \to \infty$ limit of a coupling with bifundamental "messenger" fields.

• The two AdS spaces ("Universes") are coupled via their common boundary.

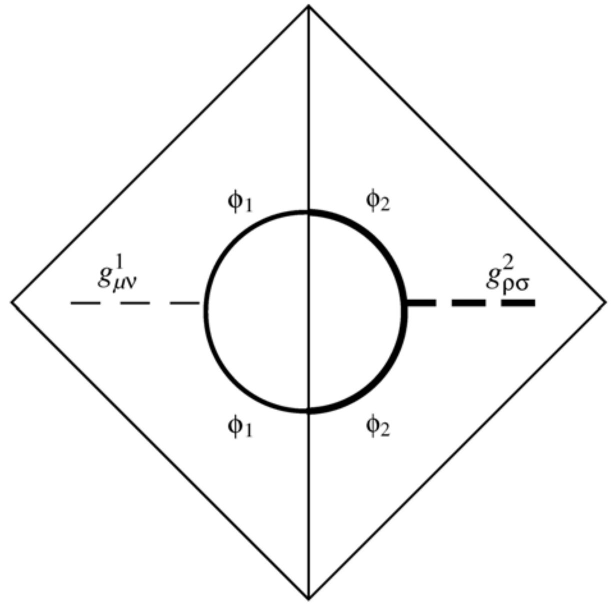
• One of the two gravitons remains massless while the other acquires a mass at one-loop.

Kiritsis ('05), Aharony+Adam+Karch ('05), Kiritsis+Niarchos ('08)

The reason is that now only one of the stress tensors is conserved and the graviton mass is proportional to the anomalous dimension of the spin-two operator.

$$M_g^2\ell^2 = h^2\left(\frac{1}{c_1}+\frac{1}{c_2}\right)\frac{\Delta_1\Delta_2 d}{(d+2)(d-1)} \sim h^2\left(\frac{1}{N_1^2}+\frac{1}{N_2^2}\right)\frac{\Delta_1\Delta_2 d}{(d+2)(d-1)}$$

with $C_i \sim N_i^2$.



- In the bulk theory, $\mathcal{O}_1 \sim \Phi_1$ and $\mathcal{O}_2 \sim \Phi_2$, with the same mass.

- The double trace deformation induces mixed boundary conditions for Φ_1, Φ_2

Witten ('01), Berkooz+Sever+Shomer ('01), Muck ('02)

- This allows the one-loop diagram that provides a term $g_1^{\mu\nu} g_{2,\mu\nu}$ mixing the two gravitons.

- This generalizes to multiple QFTs.

• According to intuition from string theory and holography, If a large-N CFT is coupled at UV by multiplet trace interactions to a finite-N QFT, the bulk picture is of a "probe brane" carrying the finite-N QFT at the boundary of the bulk space generated by the large-N CFT. The bulk graviton couples to the stress tensor of the probe-brane.

Therefore:

• large-N/large-N $\to g_1^{\mu\nu} g_{2,\mu\nu}$

• large-N/finite-N $\to g_1^{\mu\nu} T_{2,\mu\nu}$

• finite-N/finite-N $\to T_1^{\mu\nu} T_{2,\mu\nu}$

• If several large-N CFTs are coupled to a single finite-N QFT, then the geometrical picture is that of a brane embedded and interacting simultaneously with several distinct geometries.

• Out of all gravitons, only one is massless. Thinking about groups of CFTs and their interconnections: per connected component of CFTs there is a single unbroken diffeomorphism invariance associated to a single energy conservation law.

• Of all spin-two glueballs that are coupled via messengers to SM stress tensors,

1. Some correspond to AF theories or weakly coupled CFTs that have been destabilized: they are massive with masses of O(1).
UV Stability prefers strong coupling: all weakly coupled CFTs have relevant operators.

2. Others correspond to strongly coupled CFTs that are connected to the SM and may be connected to other large N CFTs. They contain one massless and several massive components with a mass $min\left(\frac{1}{N_i\ell_i}\right)$. Therefore the lightest graviton beyond the massless one is determined by the smallest $N_i\ell_i$ that mixes with the largest N_i.

Anomalies and extra U(1)'s

- There are several subtleties with anomalies:

♠ It can be shown that in every attempt to write the SM in terms of bi-fundamentals there is at least one and typically more than one EXTRA U(1)'s

Antoniadis+Kiritsis+Tomaras ('00), Anastasopoulos+Dijkstra+Kiritsis+Schellekens ('06)

- Unless an extra U(1) is $\sim$ B-L it is anomalous.

- If $B-L$, then it must be broken by strong dynamics beyond the SM.

- If anomalous, other degrees of freedom must cancel the anomaly. There are two possibilities:

Anastasopoulos+Bianchi+Dudas+Kiritsis, ('06)

A. The associated U(1) is broken and there are additional chiral fermions that are massive because of the Higgs effect that cancel the anomaly.

B. There is an axion-like field that breaks the "anomalous" U(1) and cancels the anomaly by $aF \wedge F$ type couplings. Consistency requires that the residual global U(1) symmetry to be broken by instanton effects. (more later)

- In all cases: at least one extra U(1) massive gauge boson is expected.RETUR

RS meets DGP

• The standard DGP analysis is valid in 5 flat dimensions.

• In the standard fine-tuned RS model, we can superpose an extra four-dimensional Einstein term $M_P^2\ R_4$ coming from SM loops.

• We have two characteristic length scales, ℓ the AdS scale and $r_c = \frac{M_P^2}{M_5^3}$, the DGP scale.

♠ When $r_c \gg \ell$, gravity is 4d at all scales with 4d Plank scale equal to M_P.

♠ When $\ell \gg r_c$ gravity is 4d at length scales shorter than r_c with Planck scale M_P, 5D when the length scale is between r_c and ℓ and 4d with Planck scale $M_5^3\ell$, when the length scale is longer than ℓ.

Kiritsis+Tetradis+Tomaras ('02)

Here effectively, as there is no RS cutoff, $\ell \to \infty$, and physics is five dimensional (and AdS-like) at scales longer than r_c.

Therefore, $M_P = 10^{19}$ GeV, and

• Asking for the 5d gravity scale to be perturbative $10^{-3} eV \lesssim M_5$

• Asking for the transition scale to be at the size of the universe, $M_5 \lesssim 100 MeV$.

In total we have a range spanning 11 orders of magnitude

$$10^{-3} \ eV \quad \lesssim \quad M_5 \quad \lesssim \quad 100 \ \ MeV$$

• The dark energy observed today could be due to the DGP acceleration mechanism or mixing with other light gravitons.

Cosmology

• Cosmological evolution as felt by the SM "starts when it is coupled to gravity".

• The underlying paradigm is "mirage cosmology" understood best in its bulk formulation.

Kraus (99), Kehagias+Kiritsis (99)

• The SM branes start at $r = \Lambda_{mes}$ in the bulk and they "fall" gravitationally, inducing a cosmological evolution for the SM fields.

• As $N_c \gg 1$ they can be treated as probe branes in the background geometry.

• We can "start" cosmological evolution by an initial SM energy density $> \Lambda_{mes}^4$. This triggers the gravitational couplings and affects the evolution of the SM energy density

• The SM brane "falls" in the bulk.

• The detailed analysis of various effects of the cosmological evolution remains to be done

Plan of the presentation

- Title page 1 minutes
- Introduction 2 minutes
- The Logic 3 minutes
- The couplings of the SM 4 minutes
- QFT vs ST 6 minutes
- The UV landscape of 4D gauge theories 10 minutes
- The leading IR interactions. 14 minutes
- A messenger friendly SM 18 minutes
- The equivalence principle: I 19 minutes
- Maldacena vs Randall+Sundrum 22 minutes
- DGP Revisited 25 minutes
- The equivalence principle(II). 26 minutes
- The Axion 28 minutes
- Hyper-unification 29 minutes
- Outlook 30 minutes

- String Theory and gravity 33 minutes
- Strings/gravity and 4D gauge theories 48 minutes
- Generalized Bank-Zaks fixed points 51 minutes
- Bank-Zaks-YM theories 54 minutes
- Bosonic String or Superstring 57 minutes
- Many string universes and their mixing 67 minutes
- Anomalies and extra U(1)'s 69 minutes
- RS meets DGP 72 minutes
- Cosmology 75 minutes